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On the short distance nonperturbative corrections in heavy quark expansion

S. Arunagiri

Department of Nuclear Physics, University of Madras

Guindy Campus, Chennai 600 025, Tamil Nadu, INDIA

Abstract

We estimate the renormalon corrections to the inclusive decay rate of heavy hadrons. We assume the gluon mass term $\lambda^2 \gg \Lambda^2_{QCD}$ to imitate the short distance nonperturbative effects. It is found that the the inclusive decay rates are corrected by an amount of about 0.2 Γ_0 for B meson and 0.21 Γ_0 for baryon. This is significant in view of the discrepancy of lifetimes of B and Λ_b.

The divergence of perturbation theory at large order brings in an ambiguity to physical quantities specified at short distances. According to the present understanding, the ambiguity is given by a class of renormalon diagrams which are chain of n-loops in a gluon line. The phenomenon is deeply connected with the operator product expansion (OPE). The perturbative part of the OPE receives the renormalons corrections [1]. Since in the OPE the first power-suppressed nonperturbative term is absent and the renormalons corrections constitute short distance nonperturbative effect, it is much meaningful beyond mere large order corrections.

The phenomenology of the power corrections is significant for the heavy quark expansion (HQE) to describe the inclusive decays of heavy hadrons by an expansion in the inverse powers of the heavy quark mass, m_Q. As the inclusive decay rate of heavy hadrons scales like fifth power of the heavy quark mass, the power corrections arise due to momenta smaller than the heavy quark mass. However, these IR renormalons would, being nonperturbative effect, have greater influence in the HQE prediction of quantities of interest. These short distance nonperturbative effects can be sought for explaining the smaller lifetime of Λ_b. We should note that these power corrections to heavy quark decay rate represents the breakdown of quark-hadron duality. Therefore, it may shed light on the working of the assumption of quark hadron duality in the heavy quark expansion.

In this note, we present a study on the renormalons corrections considering the heavy-light correlator in the QCD sum rules approach, assuming that the nonperturbative short distance corrections given by the gluon mass that is much larger than the QCD scale. We carry out the analysis for both heavy meson and heavy baryon. Our study shows that the short distance nonperturbative corrections to the baryon and the meson differ by a small amount which is significant for the smaller lifetime of the Λ_b.

Let us consider the correlator of hadronic currents J:

$$\Pi(Q^2) = i \int d^4x e^{iqx} \langle 0|T\{J(x)J(0)\}|0\rangle \tag{1}$$

where $Q^2 = -q^2$. The standard OPE is expressed as

$$\Pi(Q^2) \approx [\text{ parton model}](1 + a_1\alpha + a_2\alpha^2 + ...) + O(1/Q^4) \tag{2}$$

where the power suppressed terms are quark and gluon operators. The perturbative series in the above equation can be rewritten as

$$D(\alpha) = 1 + a_0\alpha + \sum_{n=1}^{\infty} a_n\alpha^n \tag{3}$$

where the term in the sum is considered to be the nonperturbative short distance quantity. It is studied by Chetyrkin et al [2] assuming that the short distance tachyonic gluon mass, λ^2, imitates the nonperturbative physics of the QCD. This, for the gluon propagator, means:

$$D_{\mu\nu}(k^2) = \frac{\delta_{\mu\nu}}{k^2} \rightarrow \delta_{\mu\mu}\left(\frac{1}{k^2} + \frac{\lambda^2}{k^4}\right) \tag{4}$$

The nonperturbative short distance corrections are argued to be the $1/Q^2$ correction in the OPE.

Let us consider the assumption of the gluon mass $\lambda^2 \gg \Lambda^2_{QCD}$ which is not necessarily to be tachyonic one. The feature of the assumption can be seen with the heavy quark potential

$$V(r) = -\frac{4\alpha(r)}{3r} + kr \tag{5}$$

where $k \approx 0.2$ GeV^2, representing the string tension. It has been argued in [3] that the linear term can be replaced by a term of order r^2. It is equivalent to replace k by a term describing the ultraviolet region. For the potential in (5),

$$k \rightarrow constant \times \alpha\lambda^2 \tag{6}$$

In replacing the coefficient of the term of $O(r)$ by λ^2, we make it consistent by the renormalisation factor. Thus the coefficient $\sigma(\lambda^2)$ is given by [4]:

$$\sigma(\lambda^2) = \sigma(k^2)\left(\frac{\alpha(\lambda^2)}{\alpha(k^2)}\right)^{18/11} \tag{7}$$

Introduction of λ^2 brings in a small correction to the Coulombic term. By use of (7), we specify the effect at both the ultraviolet region and the region characterised by the QCD scale. Then, we rewrite (3) as

$$D(\alpha) = 1 + a_0\alpha\left(1 + \frac{k^2}{\tau^2}\right) \tag{8}$$

where τ is some scale relevant to the problem and k^2 should be read from (7). We would apply this to the heavy light correlator in heavy quark effective theory.

We should note that in the QCD sum rules approach, the scale involved in is given by the Borel variable which is about 0.5 GeV. But in the heavy quark expansion the relevant scale is the heavy quark mass, greater than the hadronic scale. Thus, there it turns out to be infrared renormalons effects. But, still it represents the short distance nonperturbative property, by virtue of the gluon mass being as high as the hadronic scale.

Meson: For the heavy light current, $J(x) = \bar{Q}(x)i\gamma_5 q(x)$, the QCD sum rules is already known [5]:

$$\tilde{f}^2_B e^{-(\bar{\Lambda})} = \frac{3}{\pi^2}\int_0^{\omega_c} d\omega\omega^2 e^{-\omega/\tau} D(\alpha) - \langle\bar{q}q\rangle + \frac{1}{16\tau^2}\langle g\bar{q}\sigma Gq\rangle + ... \tag{9}$$

where ω_c is the duality interval, τ the Borel variable and $D(\alpha)$ as defined in (3), but of the form defined in (8). It is, corresponding to the particular problem of heavy quarks, given as:

$$D(\alpha)_B = 1 + a_B\alpha\left[1 + \frac{\lambda^2}{\tau^2}\left(\frac{\alpha(\lambda^2)}{\alpha(\tau^2)}\right)^{-18/11}\right] \tag{10}$$

where $a_B = 17/3 + 4\pi^2/9 - 4\log(\omega/\mu)$, with μ is chosen to be 1.3 GeV.

With the duality interval of about 1.2-1.4 GeV which is little smaller than the onset of QCD which corresponds to 2 GeV and $\bar{\Lambda} \geq 0.6$ GeV, we get

$$\lambda^2 = 0.35GeV^2. \tag{11}$$

Baryon: For the heavy baryon current

$$j(x) = \epsilon^{abc}(\bar{q}_1(x)C\gamma_5 t q_2(x))Q(x) \tag{12}$$

where C is charge conjugate matrix, t the antisymmetric flavour matrix and a, b, c the colour indices, the QCD sum rules is given [6] by

$$\frac{1}{2}f^2_{\Lambda_b}e^{\bar{\Lambda}/\tau} = \frac{1}{20\pi^4}\int_0^{\omega_c} d\omega\omega^5 e^{-w/\tau}D(\alpha)_{\Lambda_b} + \frac{6}{\pi^4}E^4_G\int_0^{\omega_c} d\omega e^{-\omega/\tau} + \frac{6}{\pi^4}E^6_Q e^{-m_0^2/8\tau^2} \tag{13}$$

where

$$D(\alpha)_{\Lambda_b} = 1 - \frac{\alpha}{4\pi}a_{\Lambda_b}\left(1 + \frac{\lambda^2}{\tau^2}\right) \tag{14}$$

with $a_{\Lambda_b} = r_1\log(2\omega/\mu) - r2)$. With $f^2_{\Lambda_b} = 0.2\times 10^{-3}$ GeV^6, $\langle\bar{q}q\rangle = -0.24^3$ GeV^3, $\langle g\bar{q}\sigma Gq\rangle = m_0^2\langle\bar{q}q\rangle$, $m_0^2 = 0.8$ GeV^2, $\langle\alpha GG\rangle = 0.04$ GeV^4 and $D(\alpha)_{\Lambda_b}$ is expressed in accordance with power correction factor found in [6]. As in the meson case, we obtain

$$\lambda^2 = 0.4GeV^2. \tag{15}$$

Now we turn to the heavy quark expansion. The total decay rate of a weakly decaying heavy hadron is, at the leading order, given by

$$\Gamma(H_b) = \Gamma_0\left[1 - \frac{\alpha}{\pi}\left(\frac{2}{3}g(x) - \xi\right)\right] \tag{16}$$

where

$$\Gamma_0 = \frac{G_f^2 |V_{KM}|^2 m_b^5}{192\pi^3} f(x) \tag{17}$$

As already mentioned, the power corrections are given by the IR renormalons:

$$\tilde{a}\alpha \left(1 + \frac{\lambda^2}{m_b^2} \left(\frac{\alpha(\lambda^2)}{\alpha(m_b^2)} \right)^{11/18} \right) \tag{18}$$

In (16), the factor ξ corresponds to the IR renormalons which corresponds to the square root of the λ^2 term in the above equation. These corrections are estimated to be $0.1\Gamma_0$ and $0.11\Gamma_0$ for B and Λ_b respectively. This is significant in view of the discrepancy between the lifetimes of B and Λ_b being 0.2 ps^{-1} with $\Gamma(B) = 0.68$ ps^{-1} and $\Gamma(\Lambda_b) = 0.85$ ps^{-1}.

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